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Buckling strength of lipped channel column with local/distortional interactions

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Abstract

Two approaches to the choice of the most unfavourable geometric imperfections, represented by the eigenmode shapes, recently developed for GMNIA FEM analysis are studied for lipped channel columns exhibiting significant local/distortional interactions. The approaches are based on alternative imperfection measures: a) the commonly applied amplitude, b) the energy measure defined by the square root of the elastic strain energy hypothetically required to distort the originally perfect structural element into the considered imperfect shape.

Keywords: Lipped channel; Compression strength; Imperfections; Local; Distortional; Interactions

1. Introduction

In order to facilitate the choice of the most unfavourable geometric imperfections, represented by the eigenmode shapes, for the geometrically and materially non-linear FEM analysis of the strength of cold-formed steel with imperfections (GMNIA) two approaches had been recently suggested Sadovský, et al. [1]. The approaches employ two imperfection measures. Besides the commonly applied amplitude, an integral – energy measure of the initially distorted surface of a cold-formed member is adopted. The energy measure is derived as the square root of the elastic strain energy hypothetically required to distort the originally perfect shape into the considered imperfect shape of the member. The hypothetic strain energy can be directly obtained introducing the imperfection as imposed deformation in the linear elastic FEM model. For eigenmode imperfections it is in some FEM codes obtained as a by-product of the elastic eigenvalue analysis.

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When normalising geometric imperfections by the amplitude, the energy measure is used as a supporting parameter, which indicates the presence of distortional component in a single eigenmode (lower values) and shows up unrealistic amplitudes of highly distorted member shapes (high values). Generally, the smaller value of the energy measure means that less energy is required to distort the member into the eigenmode shape of given amplitude, i.e. buckling deformability of the eigenmode is greater. The quadratic functional determined by the geometric matrix of the linear elastic eigenvalue problem represents the member axial shortening corresponding to its deflection in the i^{th} eigenmode. Intuitively, one would expect that the higher the buckling load, the stiffer (axially) the member deflecting in the corresponding eigenmode. Thereby, the candidates for the most unfavourable eigenmode imperfections are to be selected from the group of eigenmodes with lower energy measures and lower levels of the corresponding buckling loads. However, normalising eigenmodes by the amplitude does not result in elastic shortenings, which decrease with the number of the eigenmode.

In the second approach suggested, the eigenmodes are normalised by the energy measure and the amplitude is used as a supporting parameter. Now the upper amplitudes indicate the presence of distortional component in single eigenmodes and their higher buckling deformability. Moreover, the higher amplitudes imply earlier onset of large deflection effects unfavourably influencing the member strength. The axial shortenings of eigenmodes are inversely proportional to the increasing buckling loads. Thus, for the approach using normalisation by the energy measure, perfect fit with the intuitive expectation is obtained. The candidates for the most unfavourable eigenmode imperfections are to be expected in the group of eigenmodes with upper amplitudes and lower levels of corresponding buckling loads. Another benefit of normalising the imperfections by the energy measure is that it essentially rules out the unrealistic amplitudes of initially highly distorted member shapes and that by the elastic stiffness matrix generating a scalar product related to the energy measure, the eigenmodes are readily combined by coefficients complying with the Pythagoras rule.

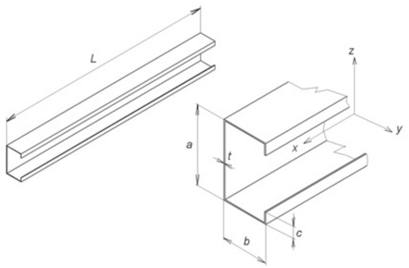

Fig. 1. Notation of channel dimensions

In the paper Sadovský, et al. [1] the test specimen ST15A90 of Young and Hancock [2] has been studied. The cross-section dimensions of the specimen shown in *Fig*. 1 are a = 98.9, b = 49.5, c = 10.7 and t = 1.5 millimetres. The specimen was brake-pressed from high strength zinc-coated Grade G450 structural steel sheets. For the yield stress, the 0.2% proof stress of 515 MPa (E = 210 GPa) resulting from web plate coupons [2] was adopted. Due to small bent radius, nor the corner properties nor residual stresses have been considered, cf. [3]. The strength of axially loaded channel with eigenmodes imperfections, simply supported of 800 mm length has been calculated by FEM codes MSC.NASTRAN and COSMOS/M applying GMNIA analysis.

The aim of the present paper is an application of the approaches to the lipped channel columns exhibiting higher level of interaction between local and distortional buckling. Retaining the above mentioned setting of computational modelling in [1] except for halving the length of the channel to 400 mm is treated as Example 1. In Example 2, additional modification aiming at increasing the proportion of distortional buckling consists in the flanges elongation to 59.5 mm and the lips shortening to 8.2 mm.

2. Example 1

The first 20 buckling loads and the energy measures $EM(\varphi_i)$ of the corresponding eigenmodes φ_i normalised by the unit amplitude (max $|\varphi_i|$ = 1 mm) calculated by MSC.NASTRAN are shown in Figure 2. The amplitude based magnitude of initial imperfections is defined as the maximum of the web distortion, the flange-lip shift parallel to the web and of the flange buckling distortion. The first two component amplitudes are of the type 1 and type 2 imperfections of Schafer and Peköz [4]. The eigenmodes are approximately classified as local, lower distortional and distortional by visual checking for the proportion of local and distortional amplitudes at coloured scales provided by the code. The modes with distortional amplitudes (type 2) of up to about 30 % of the dominating web or flange amplitude are denoted as local buckling modes. Distortional buckling modes possess dominant type 2 amplitude; remaining modes are classified as lower distortional.

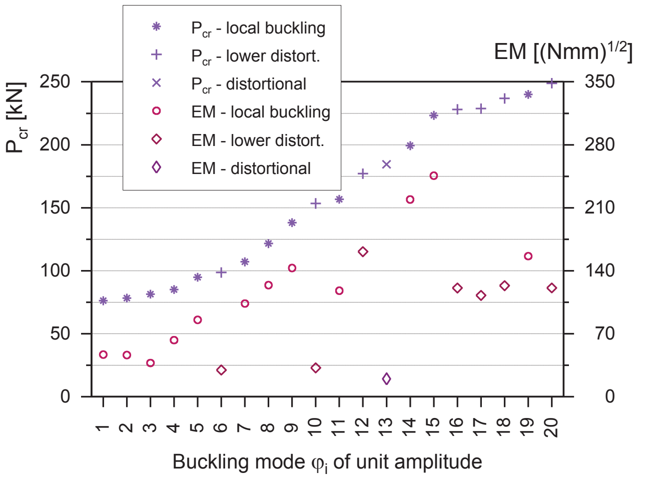

Fig. 2 Example 1: Buckling loads and the energy measure of eigenmodes normalised by the amplitude (MSC.NASTRAN).

The lowest values of the energy measure of eigenmodes normalized by the amplitude are obtained for the distortional and lower distortional modes or the lowest local buckling modes with small number of half-waves and with or without some proportion of distortional imperfection. For the higher value of the energy measure of the 12th eigenmode with one central distortional half-wave along the channel length is responsible the web distortion of 13 half-waves. The potentially most unfavourable eigenmode imperfections are shown in Fig. 3 (a).

3. Example 2

3.1. Buckling loads and modes

For the cross-section with extended flanges and shortened lips, the buckling loads and the energy measures $EM(\varphi_i)$ of the eigenmodes φ_i normalised by the unit amplitude are shown in Figure 4 (MSC.NASTRAN). The lower values of the energy measure indicate the presence of distortional component in single eigenmodes as well as their higher buckling deformability. The potential most unfavourable eigenmode imperfections are shown in Figure 3 (b). Note that starting from the 15th eigenmode altogether five modes up to the 20th mode are highly distorted with local buckling of the flanges of five to eleven half-waves, distortional components and two half-waves across the web width. Checking the MSC NASTRAN results with the code COSMOS/M has shown very good correspondence between buckling loads, energy measure calculations and eigenmode shapes.

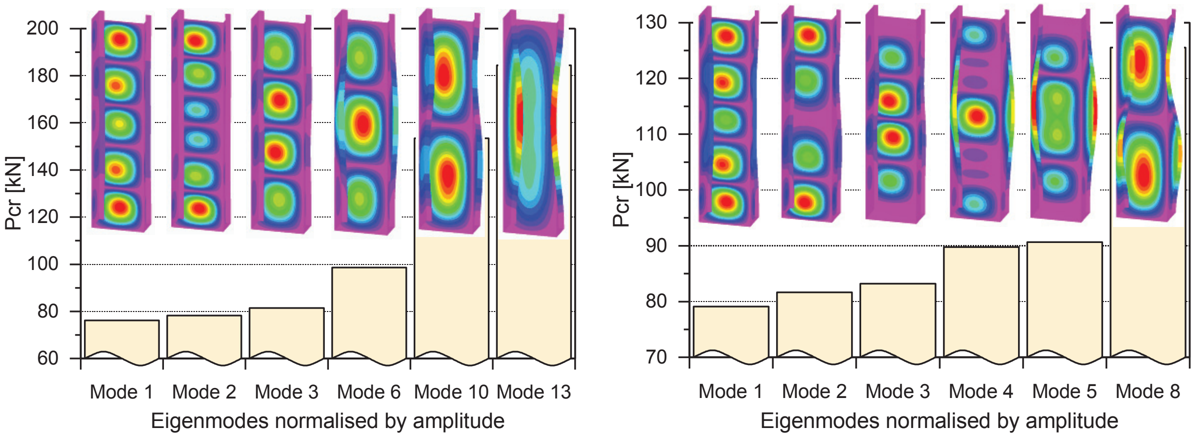

Fig. 3. (a) Example 1: Buckling loads and eigenmodes; (b) Example 2: Buckling loads and eigenmodes

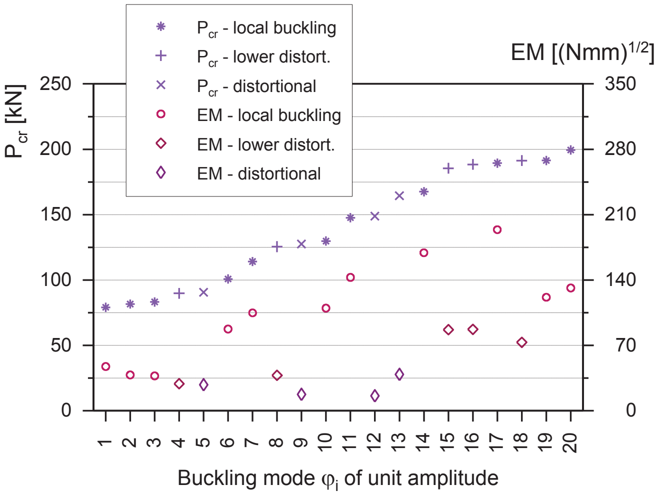

Fig. 4 Example 2: Buckling loads and the energy measure of eigenmodes normalised by the amplitude (MSC.NASTRAN).

3.2. Ultimate loads and modes

Ultimate loads and shapes calculated for minute imperfection amplitudes – of 0.01 mm are shown in Figure 5 (a). The lowest collapse loads are obtained for the first and second eigenmode imperfection shapes. The failure modes are distortional with approaching lips for the lowest P_{ult} values. Considering imperfections of unite amplitude – of 1 mm, the lowest P_{ult} value among the selected imperfections is obtained for the second eigenmode shape, see Figure 5 (b). However, even lower values result for some of the mentioned highly deformed imperfection modes, which suggest that their amplitude might be unrealistic. Similar conclusion has been drawn for highly deformed imperfections of thin plates and stringer stiffened cylindrical shells [5] and [6].

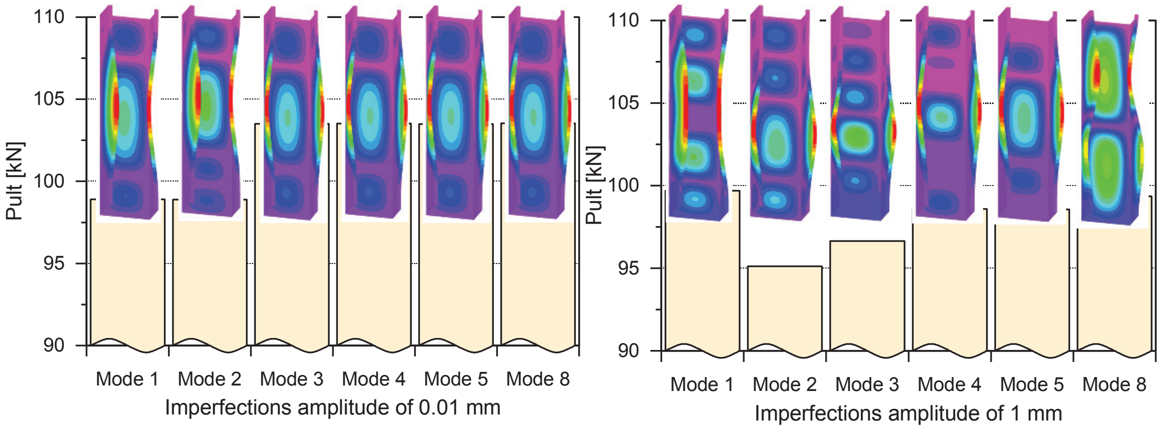

Fig. 5. (a) Example 2: Collapse loads and modes obtained for eigenmode imperfections of minute amplitudes; (b) Example 2: Collapse loads and modes obtained for eigenmode imperfections with amplitudes of 1 mm (MSC.NASTRAN).

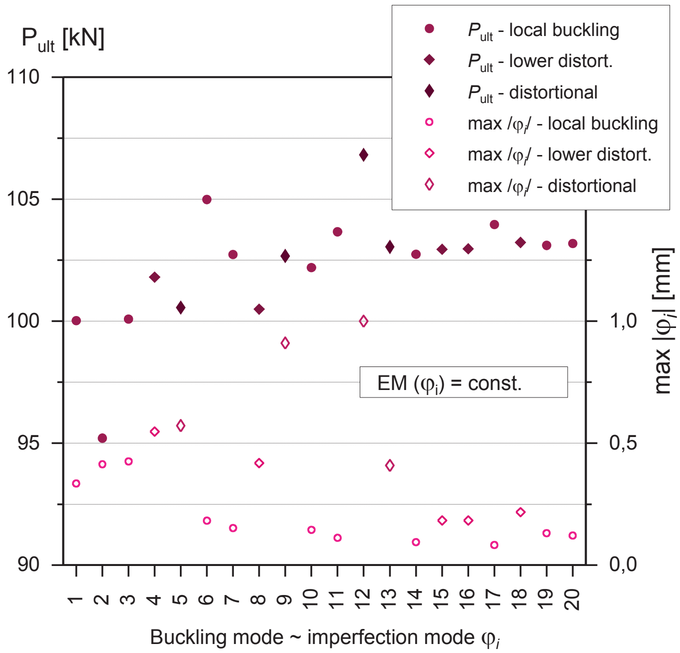

Fig. 6 Example 2: Collapse loads and amplitudes of the channel eigenmode imperfections normalised by the energy measure (MSC.NASTRAN).

The collapse loads calculated for eigenmode imperfections normalised to the level of energy measure of the 12th mode having unit amplitude of 1 mm are shown in Figure 6. The lowest P_{ult} value is found for the 2nd mode; all other collapse loads are distinctly higher. The by hollow markers plotted amplitudes of normalised eigenmodes are for highly distorted modes below 0.25 mm.

Because of space limitations, for details of FEM codes applications, the reader is referred to EUROSTEEL 2011 paper [1] and to the prepared journal paper. The same note applies for related references. As an exception the study by Schafer, Li and Moen [7] focusing on solution sensitivities of computational modelling of elastic buckling and non-linear collapse analysis for cold-formed steel members is recommended.

4. Conclusions

The paper focuses on the broader validity of two approaches, which evolve an idea of employing the elastic buckling analysis for the approximate assessment of the most unfavourable shapes of initial geometric imperfections in geometrically and materially non-linear FEM analysis of the strength of cold-formed steel. Particularly, a change of member length as well as of cross-section dimensions aiming at higher degree of distortional component in local-distortional buckling is addressed.

A crucial feature of the approaches is the introduction of the energy measure of geometric imperfections, which is used jointly with the commonly applied amplitude. Normalizing imperfections by the amplitude, the energy measure plays the role of a supporting parameter in one approach and vice versa in the other approach.

The studied examples support the conclusion [1] that normalizing geometric imperfections by the energy measure is the preferable approach. The unfavourable shapes of eigenmode imperfections are to be selected from those, which corresponding buckling loads do not exceed significantly the critical buckling load and which amplitudes are from the upper parts of their level ranges. Relatively higher amplitudes indicate the presence of distortional component in a single eigenmode. Further, normalization by the energy measure rules out imperfections with unrealistic amplitudes and the eigenmode imperfections are readily combined.

Acknowledgements

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